Constraints on the Progenitors of Type Ia Supernovae and Implications for the Cosmological Equation of State

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ABSTRACT

Detailed stellar evolution calculations have been performed to quantify the influence of the main sequence mass M_{MS} and the metallicity Z of the progenitor on the structure of the exploding WD which are thought to be the progenitors of SNe Ia. In particular, we study the effects of progenitors on the brightness decline relation $M(\Delta M_{15})$ which is a corner stone for the use of SNe Ia as cosmological yard-stick. Both the typical M_{MS} and Z can be expected to change as we go back in time. We consider the entire range of potential progenitors with 1.5 to 7 $M_\odot$ and metallicities between Z=0.02 to 1×10^{-10}. Our study is based on the delayed detonation scenario with specific parameters which give a good account of typical light curves and spectra. Based on the structures for the WD, detailed model calculations have been performed for the hydrodynamical explosion, nucleosynthesis and light curves.

The main sequence mass has been identified as the decisive factor to change the energetics of the explosion and, consequently, dominates the variations in the rise-time to decline relation of light curves. M_{MS} has little effect on the color index B-V. For similar decline rates ΔM_{15}, the flux at maximum brightness relative to the flux on the radioactive tail decreases systematically with M_{MS} by about 0.2^m. This change goes along with a reduction of the photospheric expansion velocity v_{ph} by about 2000 km/sec. A change in the central density of the exploding WD has similar effects but produces the opposite dependency between the brightness to tail ratio and v_{ph} and, therefore, can be separated.

The metallicity alters the isotopic composition of the outer layers of the ejecta. Selective line blanketing at short wavelengths decreases with Z and changes systematically the intrinsic color index B-V by up to -0.06^m, and it alters the fluxes in the U band and the UV. The change in B-V is critical if extinction corrections are applied. The offset in the calibration of $M(\Delta M_{15})$ is not monotonic in Z and, in general, remains $\leq 0.07^m$.

We use our results and recent observations to constrain the progenitors, and to discuss evolutionary effects of SNe Ia with redshift. The narrow spread in the fiducial rise-time to decline relation in local SNe Ia restricts the range of main sequence masses to a factor of 2. The

upper limit of 1 day for the difference between the local and distance sample support the need for a positive cosmological constant. The size of evolutionary effects are small ($\Delta M \approx 0.2^m$) but are absolutely critical for the reconstruction of the cosmological equation of state.

Subject headings: supernovae - cosmological parameters - distance scale

1. Introduction

The last decade has witnessed an explosive growth of high-quality data for supernovae both from the space and ground observatories with spectacular results, and new perspectives for the use of SNe Ia as cosmological yard sticks and for constraining the physics of supernovae. One of the most important new developments in observational supernova research was to establish the long-suspected correlation between the peak brightness of SNe Ia and their rate of decline, $M(\Delta M_{15})$, by means of modern CCD photometry (Phillips 1993). SNe Ia have provided new estimates for the value of the Hubble constant (H_0) based on a purely empirical procedure (Hamuy et al. 1996ab, Riess, Press & Kirshner, 1996), and on a comparison of detailed theoretical models with observations (Höflich & Khokhlov 1996, hereafter HK96; Nugent et al. 1997). The values obtained are in good agreement with one another. More recently, the routine successful detection of supernovae at large redshifts, z (e.g. Perlmutter et al. 1995, 1997; Riess et al. 1998; Garnavich et al. 1998), has provided an exciting new tool to probe cosmology. This work has provided results that are consistent with a low matter density in the Universe and, most intriguing of all, yielded hints for a positive cosmological constant Ω_Λ of ≈ 0.7. It is worth noting that the differences in the maximum magnitude between Ω_Λ=0 and 0.7 is $\approx 0.25^m$ for redshifts between 0.5 to 0.8. These results prompted the quest for the nature of the the 'dark' energy, i.e. cosmological equation of state. Current candidates include a network of topological defects such as strings, evolving scalar fields (i.e. quintessence), or the classical cosmological constant. For a recent review, see Ostriker & Steinhardt (2001), and Perlmutter, Turner & White (1999b). To separate between the candidates by SNe Ia, the required accuracy has to be better than 0.05 to 0.1^m (Albrecht & Weller 2000). The results on Ω_Λ and future projects to measure the cosmological equation of state depend on the empirical $M(\Delta M_{15})$ which is calibrated locally. This leaves systematic effects as the main source of concern.

Indeed, there is already some evidence that SNe Ia undergo evolution. It has been argued, that the local SN Ia sample covers all the possible variations that may come from different progenitors, different explosion mechanisms and environments, etc.. For local SNe Ia, the observational and statistical characteristics depend on their environment. They occur less often in ellipticals than in spirals, and the mean peak brightness is dimmer in ellipticals (Branch et al. 1996; Wang, Höflich & Wheeler 1997; Hamuy et al. 2000). In the outer part of spirals the brightness is similar to ellipticals while, in more central regions, both intrinsically brighter and dimmer SNe Ia occur (Wang et al. 1997). These dependencies show us that SNe Ia likely depend on the underlying population and may undergo evolution. If the evolution realizes then we have to know it and take it into account going back in time. Otherwise we can not *safely* use a local calibration. In principle, more distant sample could come from younger and more metal-poor progenitors, or the dominant explosion scenario may change.

There is general agreement that SNe Ia result from some process of combustion of a degenerate white dwarf (Hoyle & Fowler 1960). Within this general picture, three classes of models have been considered: (1) An explosion of a CO-WD, with mass close to the Chandrasekhar mass, which accretes mass through Roche-lobe overflow from an evolved companion star (Whelan & Iben 1973). The explosion is then triggered

by compressional heating near the WD center. (2) An explosion of a rotating configuration formed from the merging of two low-mass WDs, caused by the loss of angular momentum due to gravitational radiation (Webbink 1984, Iben & Tutukov 1984, Paczyński 1985). (3) Explosion of a low mass CO-WD triggered by the detonation of a helium layer (Nomoto 1980, Woosley et al. 1980, Woosley & Weaver 1986). Only the first two models appear to be viable. The third, the sub-Chandrasekhar WD model, has been ruled out on the basis of predicted light curves and spectra (Höflich et al. 1996b, Nugent et al. 1997).

Delayed detonation (DD) models (Khokhlov 1991, Woosley & Weaver 1994, Yamaoka et al. 1992) have been found to reproduce the optical and infrared light curves and spectra of 'typical' SNe Ia reasonably well (Höflich 1995, hereafter H95; Höflich, Khokhlov & Wheeler 1995, hereafter HKW95; HK96; Fisher et al. 1998; Nugent et al. 1997; Wheeler et al. 1998; Höflich et al. 2000; Lentz et al. 2001; Gerardy et al. 2001). This model assumes that burning starts as subsonic deflagration and then turns to a supersonic, detonative mode of burning. Due to the one-dimensional nature of the model, the speed of the subsonic deflagration and the moment of the transition to a detonation are free parameters. The moment of deflagration-to-detonation transition (DDT) is conveniently parameterized by introducing the transition density, $\rho_{\rm tr}$, at which DDT happens. The amount of ^{56}Ni, M_{56Ni}, depends primarily on ρ_{tr} (H95; HKW95; Umeda et al. 1999), and to a much lesser extent on the assumed value of the deflagration speed, initial central density of the WD, and initial chemical composition (ratio of carbon to oxygen). Models with smaller transition density give less nickel and hence both lower peak luminosity and lower temperatures (HKW95, Umeda et al. 1999). In DDs, almost the entire WD is burned, i.e. the total production of nuclear energy is almost constant. This and the dominance of ρ_{tr} for the ^{56}Ni production are the basis of why, to first approximation, SNe Ia appear to be a one-parameter family. The observed $M(\Delta M_{15})$ can be well understood as a opacity effect (Höflich et al. 1996b), namely, as a consequence of the rapidly dropping opacity at low temperatures (Höflich, Khokhlov & Müller 1993, Khokhlov, Müller & Höflich 1993). Less Ni means lower temperature and, consequently, reduced mean opacities because the emissivity is shifted from the UV towards longer wavelengths with less line blocking. A more rapidly decreasing photosphere causes a faster release of the stored energy and, as a consequence, steeper declining LCs with decreasing brightness. The DD models thus give a natural and physically well-motivated origin of the $M(\Delta M_{15})$ relation of SNe Ia within the paradigm of thermonuclear combustion of Chandrasekhar-mass CO white dwarfs. Nonetheless, variations of the other parameters lead to some deviation from the $M(\Delta M_{15})$. E.g. a change of the central density results in an increased binding energy of the WD and a higher fraction of electron capture close to the center which reduce the ^{56}Ni production (Höflich et al. 1996b). Because DD-models allow to reproduce the observations, we use this scenario to test the influence of the underlying stellar population on the explosion.

We note that detailed analyses of observed spectra and light curves indicate that mergers and deflagration models such as W7 may contribute to the supernovae population (Höflich & Khokhlov 1996, Hatano et al. 2000). In particular, the classical "deflagration" model W7 with its structure similar to DD models has been successfully applied to reproduce optical light curves and spectra (e.g Harkness, 1987). The evidence against pure deflagration models for the majority of SNeIa includes IR-spectra which show signs of explosive carbon burning at high expansion velocities (e.g. Wheeler et al. 1998) and recent calculations for 3-D deflagration fronts by Khokhlov (2001) which predict the presence of unburned and partial burned material down to the central regions. Currently, pure deflagration models may be disfavored for the majority of SNeIa but, clearly, they cannot be ruled out either.

Previously, Höflich, Wheeler & Thielemann (1998, hereafter HWT98) studied evolutionary effects induced by the progenitor. They calculate differences in the LC and NLTE-spectra as a function of

parameterized values of the integrated C/O ratio C/O_{Mch} and metallicity of the exploding WD. This study showed that a change of C/O_{Mch} alters the energetics of the explosion which results in an off-set of the brightness-decline relation. Most prominently, this effect can be identified by a change in the fiducial rise-time to decline relation $t_{Fmax}/t_{F\Delta M_{15}}$. The offset in $M(\Delta M_{15})$ is given by $\Delta M_V \approx 0.1\Delta t$ where Δt is the dispersion in the rise time of the 'fiducial' light curve. Aldering et al. (2000) showed that $t_{Fmax}/t_{F\Delta M_{15}}$ are identical within $\Delta t = 1d$ for the local and distant sample lending strong support for the notion that we need a positive Ω_Λ. A change in the metallicity Z causes a change in the burning conditions at the outer layers of the WD and it alters the importance of the line blanketing in the blue to the UV. Based on detailed calculations, effects of similar order have been found for both the delayed DD and the deflagration scenario (HWT98, Lentz et al. 2000). Recent studies showed the additional effect that Z will influence the final structure of the progenitor and the resulting LCs (Umeda et al. 1999, Domínguez et al. 2000, Höflich et al. 2000). However, the former two studies were restricted to the progenitor evolution whereas the latter included the connection between the progenitor and the LC but it was restricted to a progenitor of $M_{MS} = 7M_\odot$ and two metallicities, Z=0.02 and 0.004.

A more comprehensive study may be useful to eliminate potential problems due to evolution of the progenitors for the determination of the cosmological equation of state, and it may provide a direct link to the progenitors of SN Ia. In this work we connect M_{MS} and and the initial metallicity of the WD to the light curves and spectral properties of SNe Ia for the entire range of potential progenitors. In Section 2 we discuss the evolutionary properties of our models. In section 3, the results are presented for the explosion, nucleosynthesis, the light curves and spectral properties. In the final, concluding section, our model calculations are related to observations, and we discuss constraints for the progenitors and implications for the cosmological equation of state.

2. The formation of a CO WD

CO white dwarfs are the remnants of the evolution of low and intermediate mass stars (Becker & Iben 1980). Their progenitors are stars less massive than M_{up}, which is the lower stellar mass for which a degenerate carbon ignition occurs after the central helium exhaustion. The precise value of M_{up} depends on the chemical composition (see Domínguez et al., 1999, for a recent evaluation of this mass limit). It ranges between 6.5 and 8 $M_\odot$. On the base of updated theoretical stellar models of intermediate mass stars, Domínguez et al (1999) found final CO core masses in the range 0.55 - 1.04 $M_\odot$, in good agreement with semi-empirical evaluations of the WD masses (see e.g. Weidemann 1987).

In this paper, we use CO WD structures obtained by evolving models with main sequence masses M_{MS} between 1.5 and 7 $M_\odot$ and metallicities Z between 10^{-10} and 0.02. In the following a label identifies a particular progenitor model, namely $ApBzCD$ for a progenitor with a MS mass of $A.B$ $M_\odot$ and Z= $C \times 10^{-D}$.[1] These models have been obtained by means of the Frascati Raphson-Newton Evolutionary Code (FRANEC), which solves the full set of equations describing both the physical and chemical evolution of a star by assuming hydrostatic and thermal equilibrium and a spherical geometry (Chieffi & Straniero 1989, Chieffi, Limongi & Straniero, 1998). For a detailed description of the adopted input physics see Straniero, Chieffi & Limongi (1997) and Domínguez et al (1999).

Because we are interested in the final chemical structure of a CO WD, let us recall the main properties

[1] z00 stands for Z= 10^{-10}

and the major uncertainties of the evolutionary phases during which the CO core forms.

In Table 1 we show some properties of our models. In columns 1 to 9 we give: (1) the initial composition (Z and Y), (2) the model name, (3) the main sequence mass (in $M_{\odot}$), (4) the mass of the CO core at the beginning of the TP phase (in $M_{\odot}$), (5) the C abundance (mass fraction) at the center, (6) the mass (in $M_{\odot}$) of the homogeneous carbon-depleted central region, (7) the averaged C/O ratio within the final, ≈1.37 $M_{\odot}$, CO white dwarf after accretion, and (8) the ^{56}Ni mass (in in $M_{\odot}$) synthesized during the explosion. The C and O profiles (mass fraction) of the CO core for selected thermally pulsing models are shown in Figs. 1 to 4. In particular, Fig. 1 shows the changes induced by a different initial mass, while Figs. 2 and 3 illustrate the effect of the metallicity.

The internal C and O profiles of a WD are generated in three different evolutionary phases of the progenitor, namely: i) the central He burning, ii) shell He-burning during the early asymptotic-giant-branch (AGB) phase, and iii) shell He-burning during the thermally pulsing AGB phase. As illustrated in the figures, they produce three distinct layers.

The central He-burning produces the innermost homogeneous layer. This phase is initially dominated by the carbon production via the 3α reaction occurring in the center of a convective core. Once sufficient ^{12}C is synthesized, the $^{12}C(\alpha,\gamma)^{16}O$ reactions becomes competitive with 3α. Carbon is partially burned into ^{16}O. Since the opacity of a C-O mixture is larger than that of a He mixture, the extension (in mass) of the convective core increases with time. When the He mass fraction in the convective core is reduced down to ≈0.1, the He-burning is mainly controlled by $^{12}C(\alpha,\gamma)^{16}O$, and most of the oxygen in the convective core is synthesized during the late He-burning. The final abundances in the innermost region of a WD is strongly dependent on the duration of the last $5 - 10\%$ of the entire He-burning lifetime. In column 7 of table 1, we report the size (in solar masses) of this innermost homogeneous region, which corresponds to the maximum extension of the convective core.

The intermediate region of the final C/O structure is characterized by a rising carbon abundance. It is produced during the early-AGB when the He-burning shell advances in mass until it approaches the H-rich envelope. The amount of carbon (oxygen) left behind increases (decreases) due to the progressive growth of the temperature in the shell which favors the 3α reactions with respect to the α capture on ^{12}C. In addition, the short lifetime does not allow a substantial conversion of carbon into oxygen.

Finally, a thin external layer is built up during the thermally pulsing AGB. At the beginning of a thermal pulse, the large energy flux is locally produced by the 3α reactions. It induces the formation of a convective shell that rapidly overlaps the whole inter-shell region. Owing to the large He reservoir, a huge amount of carbon is produced at the base of the convective shell. After few years (10-100 yr depending on the core mass) the convective shell disappears and a quiescent He-burning takes place. It is during this longer phase that the $^{12}C(\alpha,\gamma)^{16}O$ reactions convert a certain part of the carbon produced during the pulse into oxygen. The C/O ratio left below the He-rich layer by the He burning-shell depends on the rate of the α captures on carbon. Note that the outer 'blip' in the carbon profile is the result of the last thermal pulse where the He has not yet fully depleted. The size, in mass, of this third layer depends on the duration of the thermally pulsing AGB phase. Although it is influenced by the assumed mass loss rate, it is generally believed that for M<3 $M_{\odot}$ the CO core cannot increase more than 0.1-0.2 $M_{\odot}$ during the AGB. An even smaller increase of the CO core is expected for larger M_{MS}.

The subsequent phase has been calculated by accreting H/He rich material on the resulting CO WD. Note that we have assumed that the progenitor ejects its H/He-rich envelope prior to the onset of the accretion epoch. The accreted matter has a final C/O ratio of ≈1. When the star reaches a mass close

to 1.37 $M_\odot$, ignition occurs close to the center. $\dot{M}$ has been adjusted to enforce that the thermonuclear runaway occurs at the same central density ρ_c in all models.

2.1. Dependence on the Main-Sequence Mass

In Fig. 1, the chemical structures of our models are shown as a function of M_{MS} (for Z=0.02). For low stellar masses, the core He-burning happens under lower central temperatures (see e.g. Domínguez et al. 1999). This favors the α captures on ^{12}C, which are in competition with the 3α resulting in a slightly smaller central C/O ratio for low M_{MS}.

However, the size of the region of central He-burning, M_{cen}, is increasing with M_{MS}. In a star with 7 $M_\odot$, the maximum size of the convective core is about 0.7 $M_\odot$ while, in the 1.5 $M_\odot$ model, it is only 0.25 $M_\odot$. This is the dominating factor for changes in the mean C/O ratio which, in general, produces the monotonic relation that C/O_{Mch} decreases with increasing M_{MS} (table 1).

2.2. Dependence on the initial metallicity

In Figs. 2 and 3, the chemical structures are given for various Z for stars with 3 and 5 $M_\odot$, respectively. The sizes of the innermost homogeneous region is not a monotonic function of Z. This is due to the peculiarity of very low metallicity intermediate mass stars (see Chieffi et al. 2001). In these stars (Z$\leq 10^{-10}$), the central hydrogen burning proceeds via the pp-chain instead of the CNO-cycles, as it happen for larger metallicity. It results in a smaller He-core (Ezer & Cameron 1971, Tornambé & Chieffi 1986). For solar metallicity, the higher opacities and the steeper temperature gradients produce a smaller He core (Becker & Iben 1979, 1980). In all cases the dependence on Z of the final averaged C/O ratio (column 7 of table 1) is small compared to the effect of main sequence mass. The variation with Z ranges between 5 and 10%.

2.3. Uncertainties in the final chemical structure.

For the final chemical structure, the most important uncertainty is due to the ambiguity in nuclear reaction rate of $^{12}C(\alpha,\gamma)^{16}O$. The innermost region is also sensitive to the treatment of turbulent convection which may affect the duration of the late central He-burning lifetime and the size of the convective core.

The rate of the $^{12}C(\alpha,\gamma)^{16}O$ at astrophysical energies is not well established (see e.g. Buchmman 1996, 1997). The cross section around the Gamow peak is dominated by ground state transitions through four different processes: the E1 amplitudes due to the low-energy tail of the 1^- resonance at $E_{cm} = 2.42$ MeV and to the subthreshold resonance at -45 keV, and the E2 amplitudes due to the 2^+ subthreshold resonance at -245 keV and to the direct capture to the ^{16}O ground state, both with the corresponding interference terms. Besides ground state transitions, also cascades, mainly through the E2 direct capture to 6.05 MeV 0^+ and 6.92 MeV 2^+ states, have to be considered. Obviously a higher rate ($\approx$ factor of 2) of this reaction reduces the carbon abundance left by both the core and the shell He-burning. Some indications in favor of an high value for this reaction rate comes from the rise times to maximum light in SNe Ia (HWT98), and from recent studies of pulsating WDs (Metcalfe, Winget & Charboneeau 2001).

Concerning turbulent convective mixing, it only affects the region of the WD structure produced during the core He-burning. The two major uncertainties are related to the possible existence of breathing pulses (see Castellani et al. 1985, Caputo et al. 1986) and the possible existence of a sizeable convective core overshoot. As recently pointed out by Imbriani et al. (2001), since breathing pulses increase the late core He-burning lifetime, they significantly reduce the central C/O. In this regard, they mimic the effects of a high $^{12}C(\alpha,\gamma)^{16}O$ rate. On the contrary, convective core overshoot does not affect the central C/O, but it may enlarge the size of the convective core and, in turn, may produce a larger central, C-depleted region.

In the models presented in this paper, we have neglected breathing pulses and convective core overshoot. All the models, except the 3p0z13LR, have been obtained by means of a high rate for the $^{12}C(\alpha,\gamma)^{16}O$ reaction (as given by Caughlan et al., 1985). The 3p0z13LR model has been obtained by adopting the alternative low rate presented by Caughlan & Fowler (1988). A comparison between the two models with different $^{12}C(\alpha,\gamma)^{16}O$ reaction rate is shown in Fig. 4. Changing the $^{12}C(\alpha,\gamma)^{16}O$ rate from the high to the low value drastically alters the chemical profiles of the progenitor. The Carbon abundance increases by about a factor two. At the time of the explosion, the average composition of the WD changes from oxygen-rich ($C/O_{Mch} = 0.74$) to carbon-rich ($C/O_{Mch} = 1.22$)! The consequences for the LCs are discussed below. Although a variation in the assumed convective mixing scheme may change the quantitative result of our analysis, the overall conclusions and tendencies cannot be significantly altered because its influence is limited to the innermost part of the pre-explosive structure.

3. Explosions, Light Curves and Spectral Properties

Spherical dynamical explosions and corresponding light curves are calculated. We consider delayed detonation (DD) models, because these have been found to reproduce the optical and infrared light curves and spectra of SNe Ia reasonably well (Höflich 1995b; HKW95; HK96; Nugent et al. 1997; Wheeler et al. 1998; Lentz et al. 2000; Höflich et al. 2000; Gerardy et al. 2001). Model parameters have been chosen which allow to reproduce light curves and spectra of 'typical' Type Ia Supernovae.

For our set of models, the differences can be attributed to changes in the progenitor structure of the CO-WD. As reference, we use the explosion of a progenitor with 5 $M_\odot$ at the main sequence and solar metallicity (model 5p0z22). At the time of the explosion of the WD, its central density is 2.0×10^9 g/cm^3 and its mass is close to $1.37 M_\odot$. The transition density ρ_{tr} from deflagration to detonation is chosen to be 2.3×10^7 g/cm^3.

3.1. Explosion Models

Explosion models are calculated using a one-dimensional radiation-hydro code (HK96) that solves the hydrodynamical equations explicitly by the piecewise parabolic method (Colella & Woodward 1984). Nuclear burning is taken into account using an extended network of 606 isotopes from n,p to ^{74}Kr (Thielemann, Nomoto & Hashimoto 1996 and references therein). The propagation of the nuclear burning front is given by the velocity of sound behind the burning front in the case of a detonation wave and in a parameterized form during the deflagration phase calibrated by detailed 3-D calculations (e.g. Khokhlov 1995, 2000; Niemeyer & Hillebrandt 1995). We use the parameterization as described in Domínguez & Höflich (2000). For a deflagration front at distance r_{burn} from the center, we assume that the burning

velocity is given by $v_{\rm burn} = max(v_t, v_l)$, where v_l and v_t are the laminar and turbulent velocities with

$$v_t = 0.15\ \sqrt{\alpha_T\ g\ L_f},\ with\ \alpha_T = (\alpha - 1)/(\alpha + 1)\ and\ \alpha = \rho^+(r_{\rm burn})/\rho^-(r_{\rm burn}). \qquad [1]$$

Here α_T is the Atwood number, L_f is the characteristic length scale, and ρ^+ and ρ^- are the densities in front of and behind the burning front, respectively. The quantities α and L_f are directly taken from the hydro at the location of the burning front and we take $L_f = r_{\rm burn(t)}$. The transition density is treated as a free parameter. The description of the deflagration front does not significantly influence the final structure of the explosion (Domínguez & Höflich 2000). The total ^{56}Ni production is governed by the pre-expansion of the WD and, consequently, is determined by the transition density ρ_{tr}, at which the burning front switches from the deflagration to the detonation mode (H95). From the physical point of view, ρ_{tr} should be regarded as a convenient way to adjust the amount of material burned during the deflagration phase. The value ρ_{tr} can be adjusted to produce a given amount of ^{56}Ni. This code includes the solution of the frequency-averaged radiation transport implicitly via moment equations, expansion opacities, and a detailed equation of state (see sect. 3.2). As expected from previous studies (see introduction), the overall density, velocity and chemical structures are found to be rather insensitive to the progenitor, including the production of elements.

Although explosions and light curves have been calculated for the entire set of stellar cores, we will concentrate our detailed discussion on the extreme cases and the reference model. Results for intermediate models can be understood accordingly and interpolated using the quantities given in table 1.

The final density, velocity and chemical structures and detailed production of isotopes are shown in Figs. 5, 6 and 7 for the extreme cases in metallicity (Z=0.02 and Z=10^{-10}, 5 $M_\odot$) and the extremes in M_{MS} (1.5 $M_\odot$ to 7 $M_\odot$, Z=0.02). Between 0.511 to 0.589 $M_\odot$ of ^{56}Ni are produced (table 1). The production of individual isotopes varies only by about 10 % (Fig. 7). For the reference model $5p0z22$, the final element abundances are given in Table 2. Variations in the final density and velocity structure are correspondingly small (Fig. 5).

In delayed detonations, almost the entire WD is burned. The total release of nuclear energy depends mainly on the fuel, i.e. on the integrated C/O ratio C/O_{Mch} (HWT98). However, as usual for delayed detonation models, the deflagration phase is key for our understanding of the final results. During the deflagration phase, about $0.33 M_\odot$ of fuel are burned in our models (Figs. 5 & 6). In all explosions but the progenitors with $M_{MS} = 1.5\&3 M_\odot$ with Z=0.02 and $MS = 1.5 M_\odot$ with Z=0.001, the deflagration front will propagate in the carbon-depleted layers. The amount of total energy produced during the deflagration phase and the binding energy of the progenitor determines the pre-expansion of the outer layers and, consequently, the overall chemical structure. The binding energy of the WD is dominated by the central density ρ_c at the time of the explosion. Note that the C/O ratio has little influence on the structure of the WD because the pressure is dominated by degenerate electrons and the electron to nucleon ratio Y_e is identical for ^{12}C and ^{12}O. The total energy production during the deflagration phase is governed by ρ_{tr} and by the nuclear energy release per gram, i.e. the composition. Both ρ_c and ρ_{tr} have been kept the same in all models. Variations can be understood by the change of the mean C/O ratio and the mass M_{Cen} of the central, carbon depleted region. The latter influences the temperature and, consequently, the laminar speed and the Atwood number (eq. 1). At the central layers, all the material is burned up to iron-group elements (Fig. 6). Some additional variation in the total ^{56}Ni-mass is caused by the C/O ratio of the matter burned during the detonation phase. For all models, the transition between ^{56}Ni- and Si-rich layers is between 0.58 and 0.98 $M_\odot$. For $M_{MS} = 7 M_\odot$ and, to a much lesser extend, for $M_{MS} = 5 M_\odot$, this transition region overlaps with layers of lower C-depleted (Fig. 1). From the nuclear physics, the transition

between complete and incomplete Si burning occurs in a narrow temperature range around $5 \times 10^9 K$. A locally lower C/O ratio results in lower burning temperatures. Consequently, the ^{56}Ni/Si boundary is shifted inwards and M_{56Ni} is reduced. Overall, differences between the models remain small because the nuclear energy production for C- and Oxygen burning differs only by $\approx 10\%$.

3.1.1. Dependence on the Main-Sequence Mass

An increasing M_{MS} for a given metallicity leads to changes in C_{cen} and C/O_{Mch} by 33% and -25%, respectively (table 1). Increasing M_{MS} from 1.5 to 7.0 $M_\odot$ alters the expansion velocity of a given mass element (Fig. 5, right panel) and it results in a shift of the chemical interfaces between complete, incomplete Si and explosive C burning by $\approx 1500 km/sec$ (Fig. 6).

3.1.2. Dependence on the initial metallicity Z

If we decrease the metallicity from solar ($Z = 0.02$) to $Z = 10^{-10}$ for stars with $5M_\odot$, C_{cen} and C/O_{Mch} change by as little as +10 % and -7 %, respectively. This means that the density and velocity structure of the chemical structures are virtually indistinguishable (Fig. 5). For stars with $M_{MS} \leq 3M_\odot$, variations in C_{cen} increase up to 30 % but, still, variations in C/O_{Mch} remain at a level of 10 %. The overall energetics, density and velocity structure remain mostly unchanged but the pre-expansion and, consequently, the chemical interfaces between different regimes of burning change by $\approx 200 km/sec$. For all M_{MS}, the most noticeable difference is the increasing ^{54}Fe production with Z in the layers of incomplete Si burning which changes the spectra in the blue, and in the UV (see HWT98 and below).

3.1.3. Influence of the $^{12}C(\alpha,\gamma)^{16}O$ rate

As mentioned in Sect. 2.3, there is some indirect evidence for a high cross section of this key reaction but a low rate cannot be ruled out either. The consequences of a low rate are strong. E.g., for a progenitor with $M_{MS} = 3.0M_\odot$ and $Z = 0.001$, the low rate suggested by Caughlan & Fowler (1988) will increase C_{cen} and C/O_{Mch} from 0.26 to 0.51 and 0.74 to 1.22 when compared to our favorite rate (Caughlan et al. 1985). The explosion becomes more energetic by about 20 % and the deflagration front propagates faster. The result is an increase of the ^{56}Ni production by about 10 % and a shift in the chemical interfaces by about +2500 km/sec.

3.2. Light Curves and Spectral Properties

Based on the explosion models, the subsequent expansion, bolometric and monochromatic light curves are calculated (Höflich et al. 1998, and references therein). The LC-code is the same used for the explosion, except that γ ray transport is included via a Monte Carlo scheme and nuclear burning is neglected. In order to allow a more consistent treatment of the expansion, we solve the time dependent, frequency averaged radiation moment equations. The frequency-averaged variable Eddington factors and mean opacities are calculated by solving the frequency-dependent transport equations. About one thousand frequencies (in one hundred frequency groups) and about nine hundred depth points are used. At each time step, we use

T(r) to determine the Eddington factors and mean opacities by solving the frequency dependent radiation transport equation in a comoving frame and integrate to obtain the frequency averaged quantities. The averaged opacities have been calculated assuming local thermodynamics equilibrium (LTE). Both, the monochromatic and mean opacities are calculated in the narrow line limit. Scattering, photon redistribution and thermalization terms used in the light curve opacity calculations are taken into account. In previous works, the photon redistribution and thermalization terms have been calibrated for a sample of spectra using the formalism of the equivalent two level approach (H95). Here, for increased consistency, we use the same equations and atomic models but solve the rate equations simultaneously with the light curves calculation at about every 100^{th} time step, on the expense of some simplifications in the NLTE-part compared to H95. For the opacities, we use the narrow line limit and for the radiation fields, we use the solution of the monochromatic radiation transport using ≈ 1000 frequency groups. Both the old and new approach are about equivalent in accuracy with consistent results. Most noticeable, now, B-V is bluer by about -0.03^m.

In the following discussion is based on the same set of models used in the previous section. In Figs. 8 and 9, we show the B and V light curves and some quantities at maximum light. Overall the different phases of light curves can be understood in the usual way including the bump at about day 35 which can be attributed to the change in the opacities between the layers of complete and incomplete burning (Domínguez 1991, 1994). For the reference model 5p0z22, a maximum brightness M_V of -19.20^m is reached at about 18.25 days after the explosion. The color index $B-V$ is -0.02^m.

As discussed in the introduction, the amount of ^{56}Ni, its distribution and the expansion rate of the envelope are the dominant factors which determine the absolute magnitude at maximum and the light curve shape. With all model parameters fixed but the progenitor mass and the metallicity, the differences of the light curves can be understood based on the previous discussion of the explosion models.

3.2.1. Dependence on the Main-Sequence Mass

By increasing M_{MS} from 1.5 to 7.0 $M_\odot$ for Z=0.02, both M_B and M_V decrease by $\approx 0.15^m$ consistent with a change in the ^{56}Ni mass by 14 % (Fig. 8, upper panel, and Fig. 9). The similarity in the density and velocity structures produces almost identical conditions at the photosphere. Thus, B-V is insensitive to a change in M_{MS} ($\Delta(B-V)[model-5p0z22] \leq 0.01^m$). Relative to the reference model, the rise times vary between -0.5 d (1p5z22) to +1.2d (7p0z22). The decline rate ΔM_{15} is hardly affected. A change in M_{MS} will result in an offset/dispersion in $M(\Delta M_{15})$ by up to 0.15^m. Interestingly, the fluxes on the radioactive tail are much more similar than could be expected from the spread in the ^{56}Ni masses by 14 % (Fig. 8). The change in M_{56Ni} is almost compensated by the differences in the energy deposition of γ-rays from the radioactive decay. In Fig. 10, the escape probability for hard radiation is shown as a function of time. A significant fraction of γ photons is thermalized up to about 150 to 200 days. The actual value of thermalization depends on the expansion rate which is decreasing with mass (see above). E.g. the fraction of thermalized γ photons for the models 1p5z22, 5p0z22 and 7p0z22 are 24.2 %, 25% and 27 %, respectively. The increase in the efficiency for the thermalization amounts to 11 % over the mass range and almost compensate the decrease in the ^{56}Ni mass. Note that the ratio between maximum and tail brightness is decreasing with M_V. This effect is opposite to the observed $M(\Delta M_{15})$ relation (e.g. Hamuy et al. 1996). If realized in nature, a wide range in M_{MS} would increase the dispersion in $\delta M(\Delta M_{15})$ by about 0.15^m. The presence of this effect would reveal itself by an additional change in the expansion velocity measured by the Doppler shift of lines. E.g. at maximum light, weak lines would indicate an expansion velocity at

the photosphere which is smaller by $\approx 2000 km/sec$ if we compare model 7p0z22 vs. 1p5z22. The discussion above applies to all metallicities because C_{cen} and C/O_{Mch} vary in a similar range.

3.2.2. Dependence on the initial metallicity Z

For progenitors with $M_{MS} = 5M_{\odot}$, a change in the metallicity has little effects on the energetics and, consequently, on the light curves (Fig. 8, middle panel). The most important effect is the systematic decline of B-V by $\approx 0.05^m$ when Z is changed from 0.02 to 10^{-10}. This effect can be attributed to a change of the line blending by Fe in the decoupling region of photons, i.e. the atmosphere (HWT98, Lentz et al. 2000). In B and V at maximum light, opacities are dominated by electron scattering (HKM93) but iron lines are more important in B compared to V. Consequently, a lower metallicity results in increase of the flux ratio between B and V. In the U-band and the UV, the opacities are dominated by lines. A change in the line blending will cause both a change of the radius of the flux formation and the specific flux. Therefore, a decrease in Z may result in either an in- or decrease of the monochromatic flux depending on the density structure. These findings apply to all MS-masses in our sample. To some extend, the exception are the models with $M_{MS} = 3M_{\odot}$ for which the central carbon concentration varies with metallicity and produces a change in M_{56Ni} by 3 % and a corresponding change in M_B and M_V.

3.2.3. Influence of the $^{12}C(\alpha,\gamma)^{16}O$ rate

A low nuclear rate $^{12}C(\alpha,\gamma)^{16}O$ increases the explosion energy compared to our standard rate (3p0z13LR vs. 3p0z13, see Fig. 8, lower panel). The rise time in V is reduced by 2.7 days (15.3d for 3p0z13LR vs. 18.0d for 3p0z13). The enhanced escape probability for γ-rays (Fig. 10) explains the remaining differences including the increased maximum brightness to tail ratio and the moderate increase of M_V and M_B. These results are consistent with previous findings which identified the importance of the C/O ratio for the change in the rise time of 'typical' SNe Ia (HWT98).

4. Final Discussion, Observational Constraints and Conclusions

Using a delayed detonation model and realistic structures for the exploding white dwarf, we have studied the influence of the progenitor star on the light curves and spectral properties of Type Ia Supernovae.

Stellar models: We considered stars between 1.5 to 7 $M_{\odot}$ and metallicities between $Z = 0.02$ (solar) to $Z = 10^{-10}$ which covers the full range of potential progenitors. The progenitor structures are based on detailed calculations for the stellar evolution starting at the pre-main sequence up to the thermal pulses when most of the stellar envelope is ejected and a white dwarf is formed with a mass between 0.5 and 1.0 $M_{\odot}$. Its size increases with M_{MS} and, to a lesser extend, changes with the metallicity. The subsequent accretion and burning at the surface of the WD let it grow to M_{Ch}. As a final chemical structure, the WD shows a central region of reduced C abundance between 0.21 to 0.32 originating from the convective He-burning, a layer of increased C abundance from the He-shell burning, and a layer originating for the accretion phase. The mean C/O ratio decreases by about 30 % over the entire mass range. The sensitivity on the metallicity is much weaker ($\leq 10\%$), and not monotonic.

Supernovae: Our study of SNe Ia is based on delayed detonation models because they have been found

to reproduce the monochromatic light curves and and spectra of SNe Ia reasonably well including the brightness decline relation $M(\Delta M_{15})$. Deviation from a perfect relation are due to variations in the central density, properties of the deflagration front, and the progenitor structure. All parameters but the progenitors have been fixed to produce LCs and spectra typical for 'normal' SNe Ia. In this work, rise times to maximum light are between 17.7 to 19.4 days, $M_V = -19.25^m$ to -19.11^m, and $B-V = +0.02^m$ to -0.07^m. Differences between the models and light curves remain small because the nuclear energy production by burning Carbon and Oxygen to iron-group elements differs by as little as $\approx 10\%$.

The change of M_{MS} is the decisive factor to change the energetics. The ^{56}Ni production varies by about 14 % and the velocities of the various chemical layers differ by up to 1500 km/sec. A change in the metallicity hardly affects the overall structure of the progenitor. As already discussed in detail in HWT98, its main effect is a change in the production of ^{54}Fe in the outer layers of incomplete Si burning.

As one of the main results of our study, we find that variations in M_{MS} change the shape of the LCs but hardly affects B-V whereas a change in Z affects B-V.

M_{MS} alters the $M(\Delta M_{15})$ relation which may be offset by up to 0.2^m. In addition, M_{MS} changes the flux ratio between maximum light and the radioactive tail, and it alters the photospheric expansion velocities v_{ph} measured by the Doppler shift of lines. E.g. a change in $m_V(t_{max}) - m_V(t_{max}+40d)$ by 0.2^m is coupled to a decrease in v_{ph} at maximum light by $\approx -2000 km/sec$. Note that a change in the central density ρ_c of the WD has a similar effect on $m_V(t_{max}) - m_V(t_{max}+40d)$ but with the opposite sign for Δv_{ph} (Höflich, 2001). In principle, this allows to decide whether differences in $m_V(t_{max}) - m_V(t_{max}+40d)$ between SN with similar $M(\Delta M_{15})$ are related to a change in the progenitor or the central density at the thermonuclear runaway which is sensitive to the accretion rate.

In contrast to M_{MS}, the metallicity Z hardly changes the light curve shapes ($\delta M(\Delta M_{15}) \leq 0.06^m$). It alters the line blocking by iron group elements at the photosphere mainly in the UV, U and B but hardly in V (HWT98). In the models presented here, B-V becomes systematically bluer with decreasing Z (up to $\approx 0.07^m$). Because B-V is the basic color index used to correct for interstellar extinction, the metallicity effect can systematically alter the estimates for the absolute brightness by up to 0.2^m.

^{12}C$(\alpha,\gamma)^{16}$O: At the example of a progenitor with $M_{MS} = 3M_\odot$ and Z=0.001, we have tested the influence of the low nuclear rate $^{12}C(\alpha,\gamma)^{16}O$ on the outcome. Using the lower rate suggested by Caughlan & Fowler (1988) instead Caughlan et al. (1985) results in more energetic explosions because C/O_{Mch} increases by a factor of ≈ 2. The rise times to maximum light are 15.3d instead of 18.0d. From detailed observations of nearby supernovae, Riess et al. (1999) find the following relation between the rise time t_V and the maximum brightness

$$t_V = 19.4 \pm 0.2d + (0.80 \pm 0.05d) \times (M_V + 19.45^m)/0.1^m. \qquad [2]$$

The theoretical LCs peak at $M_V = -19.21^m$ and $M_V = -19.30^m$ for $3p0z13$ and $3p0z13LR$, respectively. From the empirical fit of Riess, we would expect a rise time between 17.6 and 18.4 days which favors the high rate $^{12}C(\alpha,\gamma)^{16}O$ of Caughlan et al. (1985). Note that the uncertainties in absolute values for the rise times are $\approx$ 1 to 2 days (HWT98).

Constraints on the progenitor: Empirically, the $M(\Delta M_{15})$ has been well established with a rather small statistical error σ (0.12^m: Riess et al. 1996; 0.16^m: Schmidt et al. (1998); 0.14^m : Phillips 1999; 0.16^m : Riess et al. 1999; 0.17^m : Perlmutter et al. 1999a). From theoretical models, a spread of 0.3 to 0.5^m can be expected (Höflich et al. 1996). This may imply a correlation between free model parameters, namely the properties of the progenitors, the central density or the transition density ρ_{tr}. In this study,

we find a spread in $M(\Delta M_{15})$ of about 0.2^m for progenitors with M_{MS} between 1.5 to $7.0 M_\odot$. This may suggest a more narrow range in M_{MS} for realistic progenitors. From the fiducial rise time, progenitors with $M_{MS} \geq 3 M_\odot$ are favored. This number should be regarded as a hint because uncertainties in the LC models. Another constraint can be obtained from the observed spread in the rise-time to decline relation. Riess et al. (1999) find a spread in t_V of ± 0.4 days whereas our models show a spread of ≈ 1.7 days for $1.5 \leq M_{MS} \leq 7 M_\odot$. To be consistent with the observations, the range of main sequence masses has to be reduced by a factor of two. This range is an upper limit because additional variations in the population of SNeIa such as explosion scenarios or the central density of the WD at the time of ignition will likely result in lower correlations.

The cosmological equation of state: In the following, we want to discuss our results in context of SNe Ia as probes for cosmology and for the determination of the cosmological equation of state. We limit the discussion to the effects due to different progenitors. For a discussion of other systematic effects such as grey dust, gravitational lensing, the influence of a change in the importance of different possible scenarios (e.g merger vs. M_{Ch} models) etc. we want to refer to the growing literature in this field (e.g. Schmidt et al. 1998, HWT98, Perlmutter et al. 1999a).

Recently, there has been strong evidence for a positive cosmological constant (e.g. Perlmutter et al. 1999a, Riess et al. 1999). This evidence is based on observations that SNe Ia in the redshift range between 0.5 to 1.2 appear to be dimmer by about 0.25^m for redshifts between 0.5 to 0.8 which is comparable to the variations produced by different progenitors. However, both the internal spread in $M(\Delta M_{15})$ (see above) and the similarity in $M(\Delta M_{15})$ between the local SNe Ia and the high-z sample ($\Delta t \leq 1d$, Aldering et al. 2000) limit the likely range of models and, consequently, evolutionary effects to $\leq 0.1^m$ up to redshifts of 1. In addition, we do not expect a drastic change in the metallicity between local and supernovae at $z \leq 1$. Taking the linear dependence of B-V on the metallicity (Fig. 9) and realistic ranges for z, also reddening of 'non-grey' dust will not change the conclusion on the need for a positive cosmological constant.

As discussed in the introduction, the quest for the nature of the 'dark' energy is one of the central questions to be addressed in future (e.g. White 1998, Perlmutter et al. 1999b, Albrecht & Weller 2000, Ostriker & Steinhardt 2001). For $z \geq 1$, we can expect both very low metallicities and a significant change of the typical M_{MS}. From this study, systematic effects due to different progenitors are limited to $\approx 0.2^m$. Therefore, without further corrections for the progenitor evolution, some of the alternatives for the nature of the 'dark energy' may be distinguished without correction for evolution. However, for a more detailed analysis, an accuracy of about 0.05^m (Weller & Albrecht 2001) is required. In this paper, we have shown how a combination of spectral and LC data or different characteristics of the LC can help to achieve this goal.

Limitations: Finally, we also want to mention the limitations of this study. Qualitatively, our results on the Z dependence agree with a previous study (Höflich et al. 2000) which was based on a progenitor with $M_{MS} = 7\ M_\odot$ calculated by Nomoto's group (Umeda et al. 1999). The relation between C/O_{Mch} and the offset in the $M(\Delta M_{15})$ relation has been confirmed. However, the influence of Z on C/O_{Mch} was found to be about twice as large, and the central C concentrations are systematically larger. The differences point towards a general problem. The details of the central structure and evolution in the convective He burning core depend sensitively on the treatment of convection, semi-convection, overshooting, and breathing pulses (Lattanzio 1991, Schaller et al. 1991, Bressan et al. 1993, Vassiliadis & Wood 1993). For a detailed discussion, see Domínguez et al. (1999). In particular, the central C concentration may vary between 0.1 and 0.5. We want to note, that our value is consistent with direct measurements of the central C/O ratio found by the analysis of pulsational modes of WDs (Metcalfe et al. 2001). These uncertainties will affect

the efficiency to separate the contribution of M_{MS} and Z, respectively, i.e. the reason for C/O_{Mch} but not the observable relations for LCs and spectra.

We provide limits on the size of evolutionary effects due to M_{MS} and metallicity of the progenitor ($\Delta M \approx 0.2^m$). Other evolutionary effects may be due to a systematic change in the dominant progenitor scenario (e.g. mergers vs. single degenerate) or the typical separation in binary systems which contribute to the SNe Ia at a given time. The latter may alter the accretion rates and, consequently, the central densities of the WD at the time of the thermonuclear runaway.

We did not consider the effect of the progenitor and of its pre-conditioning just prior to the explosion on the propagation of the burning front and, in particular, on the deflagration to detonation transition or, alternatively, the phase of transition from a slow to a very fast deflagration (Hillebrandt, 1999 private communication). Although the model parameters have been chosen to allow for a representation of “typical” SNe Ia, more comprehensive studies and detailed fitting of actual observations are needed e.g. to detangle effects due to a change in the ignition density vs. the progentor. In particular, observations of local SNe Ia have to be employed to narrow down and test for the proposed range of flux ratio between maximum and tail, and its relation to the expansion velocities.

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Table 1. Properties of the models

	Model	$M_{MS}(M_\odot)$	$M^{TP}_{CO}(M_\odot)$	C_{cen}	$M_{cen}(M_\odot)$	C/O_{Mch}	^{56}Ni $(M_\odot)$
Z=0.02	1p5z22	1.5	0.55	0.21	0.27	0.75	0.589
Y=0.28	3p0z22	3.0	0.57	0.21	0.28	0.76	0.584
	5p0z22	5.0	0.87	0.29	0.46	0.72	0.561
	7p0z22	7.0	0.99	0.28	0.70	0.60	0.516
$Z=10^{-3}$	1p5z13	1.5	0.59	0.24	0.31	0.76	0.587
Y=0.23	3p0z13	3.0	0.77	0.26	0.39	0.74	0.567
Y=0.23	5p0z13	5.0	0.90	0.29	0.58	0.66	0.541
	6p0z13	6.0	0.98	0.29	0.71	0.60	0.522
	LOW Rate						
	3p0z13LR	3.0	0.76	0.51	0.38	1.22	0.620
$Z=10^{-4}$	3p0z14	3.0	0.80	0.27	0.41	0.73	0.568
Y=0.23	5p0z14	5.0	0.90	0.29	0.58	0.65	0.541
	6p0z14	6.0	0.99	0.28	0.72	0.59	0.511
$Z=10^{-10}$	5p0z00	5.0	0.89	0.32	0.49	0.70	0.549
Y=0.23	7p0z00	7.0	0.99	0.31	0.59	0.62	0.525

Table 2. Element production (in $M_\odot$) of the reference model $5p0z22$.

He	C	O	Ne	Na	Mg	Si
6.62E-04	1.19E-02	9.18E-02	5.34E-03	4.91E-05	1.82E-02	2.61E-01
P	S	Cl	Ar	K	Ca	Sc
2.51E-05	1.59E-01	4.00E-06	3.28E-02	1.99E-06	3.44E-02	1.02E-08
Ti	V	Cr	Mn	Fe	Co	Ni
1.61E-05	9.07E-04	6.56E-04	2.68E-02	6.57E-01	6.15E-03	6.47E-02

Fig. 1.— Final chemical Carbon (solid) and Oxygen (dotted) profiles in the central region of stars between 1.5 and 7 $M_{\odot}$ for solar abundances Z = 0.02.

Fig. 2.— Same as Fig. 1 but for stars with 3 $M_{\odot}$ and metallicities Z between 10^{-10} and 0.02.

Fig. 3.— Same as Fig. 1 but for stars with 5 $M_{\odot}$ and metallicities Z between 10^{-10} and 0.02.

Fig. 4.— Influence of the nuclear reaction rate of $^{12}C(\alpha,\gamma)^{16}O$ on the final chemical profiles of C(solid) and O(dotted) for a star with $3M_{\odot}$ and Z=0.001. The high and low rates are taken from Caughlan et al. (1985) and Caughlan & Fowler (1988), respectively.

Fig. 5.— Final density (left scale) relative to ρ at the center and velocity profiles (right scale in 1000 km/sec) of the delayed detonation models. The results are given for progenitors with $M_{MS} = 5M_{\odot}$ with $Z = 10^{-10}, 0.02$ (5p0z22+5p0z00, left panel), and for progenitors with M_{MS}= 1.5 & 7 $M_{\odot}$ with Z=0.02 (1p5z22+7p0z22, right panel). The velocity and density of model $1p5z22$ correspond to the higher and lower function, respectively. For the same M_{MS} but different Z, the curves are indistinguishable.

Fig. 6.— Final chemical profiles for delayed detonation models of progenitors with MS masses between 1.5 and 7 $M_{\odot}$.

Fig. 7.— Isotopic abundances relative to solar for models with progenitors of various MS masses and metallicities. Isotopes of the same element are connected by lines.

Fig. 8.— B and V light curves for DD-models with progenitors of various M_{MS} (upper panel) and metallicities (middle panel). In the lower panel, we show the influence of the nuclear reaction rates according to Caughlan et al. (1985, 3p0z13) and Caughlan & Fowler (1988, 3p0z13LR).

Fig. 9.— Influence of M_{MS} (left) and metallicity (right) on B (—), V (····) and B-V (- - -) at maximum light. All quantities are given relative to the reference model $5p0z22$. In the right panel, the numbers 1,2,3,4 refer to Z of 0.02, 0.001, 0.0001 and 10^{-10}, respectively.

Fig. 10.— Fig. 10: γ-luminosity normalized to the instantaneous energy production by radioactive decays (in %) as a function of time for the reference model 5p0z22 (upper left). For other models, the difference is shown relative to model 5p0z22.

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